PARYLENE ACCELEROMETER UTILIZING SPIRAL BEAMS

S. Aoyagi [1], K. Makihira[1], D. Yoshikawa [1] and Y.C. Tai[2]
[1]Kansai University, JAPAN
[2]California Institute of Technology, USA

ABSTRACT

This paper reports a Parylene accelerometer utilizing spiral beams. Since Parylene has intrinsic tensile stress, the resonant frequency ω_n of sensor structure is higher than that under no tensile stress. Considering the sensitivity of accelerometer is $1/\omega_n{}^2$, the investigation of ω_n of a suspended structure supported by straight beams is carried out both theoretically and experimentally. As a result, it is proved that comparatively long beams are necessary for realizing the high sensitivity of a Parylene sensor with tensile stress. A spiral beam is effective for not only realizing a long beam in a limited space, but also realizing stress relaxation. Both Parylene accelerometer with straight beams and that with spiral beams are fabricated. Sensitivity of them is characterized, and the effectiveness of utilizing spiral beam is confirmed.

1. INTRODUCTION

Parylene is polymer material expected to be applied in micromachine field, since it is bio-compatible and can be conformally deposited at room temperature. Many sensors and actuators using Parylene are under investigation and reported **[1]**. Authors have already reported a surface micromachinable Parylene accelerometer comprising a dielectric seismic mass and comb-shaped planar capacitor underneath it as shown in **Fig. 1** **[2]**. Parylene has intrinsic tensile stress on account of mismatch of thermal coefficient of expansion (TCE) between substrate (silicon, silicon dioxide, etc.) and Parylene deposited on it **[3]**. This tensile stress plays important role in defining mechanical characteristics of a MEMS structure. In the case of Parylene accelerometer, the resonant frequency ω_n of sensor structure is higher than that under no tensile stress. Since the sensitivity of accelerometer is $1/\omega_n^2$ **[4]**, the sensitivity under tensile stress is lower than that under no tensile stress. Therefore the estimation of ω_n under tensile stress is important for designing the size of the structure.

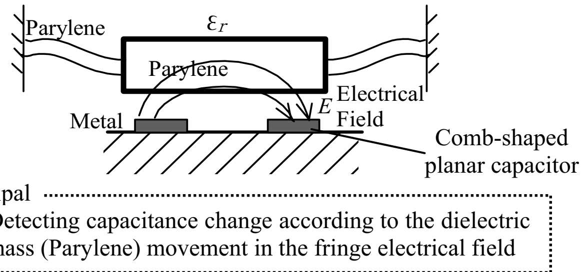


Figure 1: Measuring principles of Parylene accelerometer

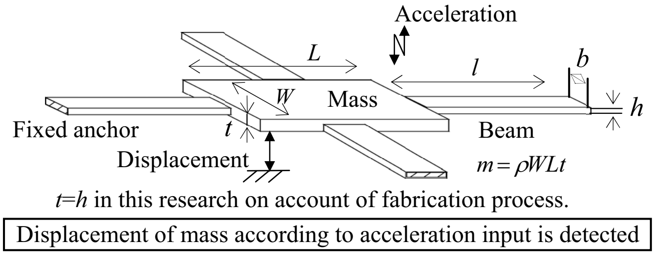


Figure 2: Accelerometer comprising a proof mass and support beams

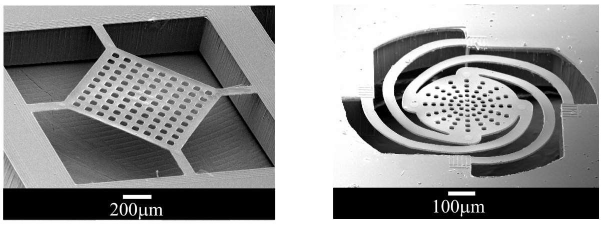
Assuming the structure shown in **Fig. 2**, FEM simulation has already carried out and it was proved $\omega_n \propto 1/l^{0.4}$ holds true under tensile stress **[5]**, while $\omega_n \propto 1/l^{1.5}$ holds true under no tensile stress according to the theory of strength of materials **[6]**, where l is beam length. In this paper, first the experimental verification of this simulation result is investigated. Complete free standing Parylene structures are fabricated. Vibrations of them are observed by a LDV (Laser Doppler Vibrometer) and their resonant frequencies are obtained. These results have good agreement with simulation results. This means large l is necessary for realizing high sensitivity of Parylene sensor with tensile stress.

Second this paper proposes a suspended structure supported by spiral beams to overcome this problem. Spiral beam is effective for not only realizing a long beam in a limited space, but also realizing stress relaxation. It is experimentally proved by a LDV that the structures with spiral shaped beams are effective for lowering resonant frequency.

Several accelerometers with straight beams and with spiral beams are fabricated. The sensitivity is characterized in vacuum condition. These sensors basically can detect acceleration with good linearity. And it is experimentally confirmed that the sensitivity of the structures with spiral shaped beams is higher than that of the structures with normal straight beams.

2. RESONANT FREQUENCY OF PARYLENE SUSPENDED STRUCTURE UNDER TENSILE STRESS

The resonant frequency ω_n of Parylene suspended structures is investigated both theoretically and experimentally. The plate vibration theory cannot be simply applied to the Parylene suspended structure, since Parylene has severe intrinsic tensile stress. Therefore FEM (Finite



(a) Structure with straight beams (b) Structure with spiral beams

Figure 3: SEM images of free standing Parylene structure

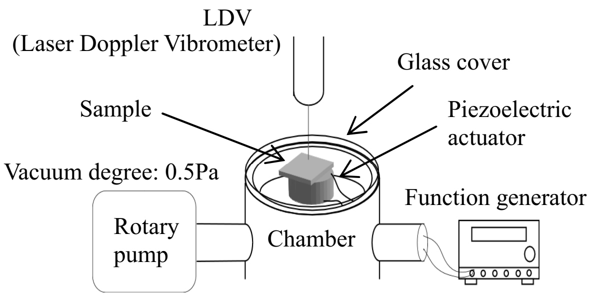


Figure 4: Experimental setup for resonant frequency measurement

Element Method) simulation has been carried out **[5]**. FEMLAB by Comsol, Inc. is adopted as a FEM software **[7]**. It was proved $\omega_n \propto 1/l^{0.4}$ holds true under tensile stress, while $\omega_n \propto 1/l^{1.5}$ holds true under no tensile stress according to the theory of strength of materials **[6]**. It means that rather long beam is necessary for lowering the resonant frequency, which also leads to increasing the sensitivity of Parylene accelerometer.

Next, the resonant frequencies of Parylene suspended structures are investigated experimentally. Complete free standing Parylene structures are fabricated as shown in **Fig. 3**. Parylene is deposited on oxidized silicon substrate, patterned by O_2 plasma, and backside of substrate is etched away by ICP-DRIE. Vibrations of these structures are observed by a LDV as shown in **Fig. 4**. Thin Al (Aluminum) is deposited at a part of structure surface in order to reflect a laser beam of the LDV. A vacuum chamber is specially developed and employed in order to decrease the influence of air damping effect. This vacuum degree is about 0.5 Pa. Specimens are set on a piezoelectric actuator. Changing the driving frequency of this actuator, the amplitude of the center of the plate of the proof mass is measured. An example of frequency response is shown in **Fig. 5**. In this case the mass size of measured structure is 1000x1000x5 μm and straight beam size of that is 200x50x5 μm. According to this figure, it is found that the resonant frequency is about 14.5 kHz. Comparing this result with the simulation result, the tensile stress is estimated to be about 10 MPa. This value agrees well with actual tensile stress measured by a rotational tip **[3]**.

As for structures with straight beams, the relationship between $f_n(=\omega_n/2\pi)$ and l is shown in **Fig. 6**. In this case

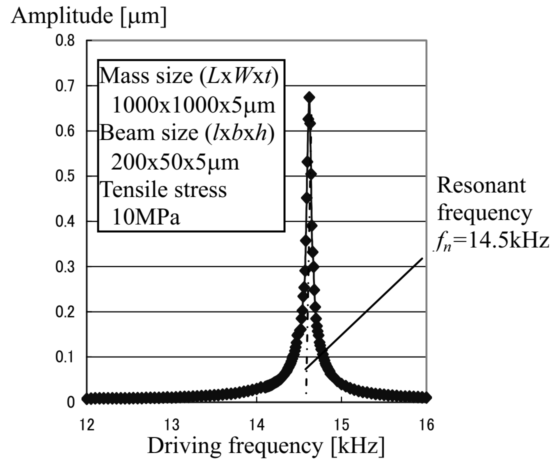


Figure 5: Frequency response

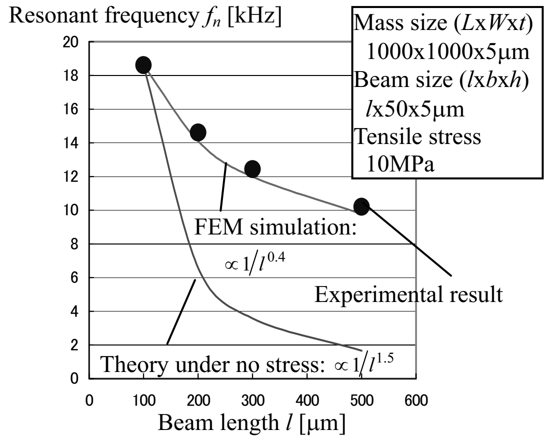


Figure 6: The relationship between resonant frequency and beam length

Table 1: Comparison of resonant frequency between experimental results and simulated ones

Beam shape	Mass size (radius)	Beam size (lxb)	Experimental result [kHz]	Simulation result		
				stress : 0MPa	stress : 5MPa	stress : 10MPa
Spiral	500μm	600x50μm	4.1	2.8	13.3	18.4
	500μm	1000x50μm	1.6	1.1	8.2	11.5
	1000μm	900x100μm	1.8	0.8	6.5	9.0

Actual tensile stress of Parylene film outside the structure area is about 10MPa.

Thickness of these structures is 5μm for all data.

the mass size is 1000x1000x5 μm and the beam width and thickness are fixed to 50 μm and 5 μm respectively. Seeing this figure, it is found that the resonant frequency is proportional to $1/l^{0.4}$. It proves the validity of the simulated relation of $\omega_n \propto 1/l^{0.4}$. On the other hand, $\omega_n \propto 1/l^{1.5}$ holds true under no tensile stress. From these result, it is confirmed that much longer beam is necessary for getting lower resonant frequency.

As for structures with spiral beams, **Table 1** shows the comparison between experimental f_n and simulated ones.

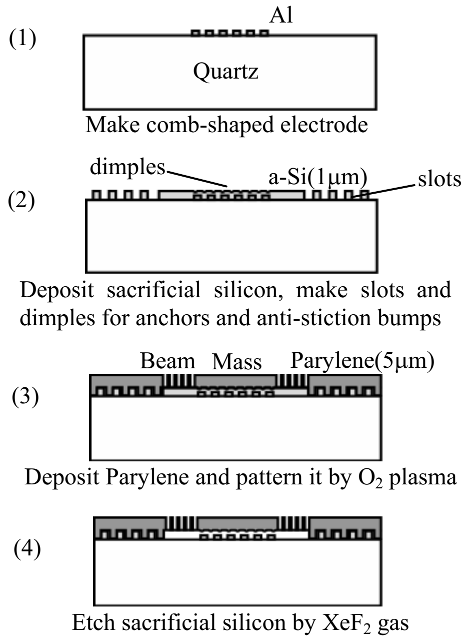


Figure 7: Process flow of Parylene accelerometer

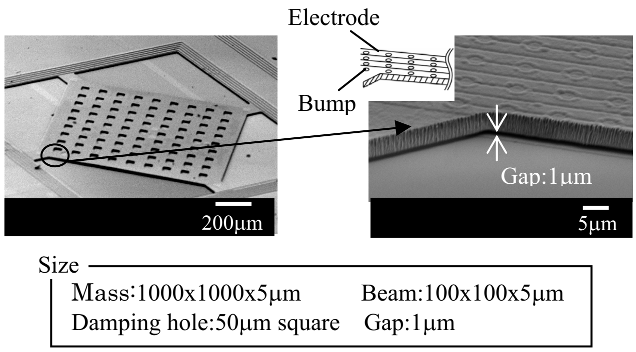


Figure 8: SEM image of fabricated Parylene accelerometer

This simulation assumes that conformal tensile stress exists everywhere in the structure. The tensile stress in this spiral structure is less than 5 MPa (near no stress) according to this result. However, actual tensile stress of Parylene film outside the structure area is measured by rotational tip **[3]**, and is about 10 MPa. This means tensile stress is much relaxed by using spiral beams, which is effective for decreasing f_n and increasing the sensitivity. From these results, the structure with spiral shaped beam is useful for Parylene accelerometer.

3. PARYLENE ACCELEROMETER

Several accelerometers made of Parylene are fabricated practically. The fabrication process flow is shown in **Fig. 7**. The process is as follows: A quartz wafer is prepared as the substrate. Al (Aluminum) is deposited and patterned for comb-shaped electrode (Fig. (1)). Amorphous silicon (1 μm) is deposited as a sacrificial layer. This sacrificial layer is patterned for making slots and dimples. Parylene is deposited on this layer afterward, forming anchors at slots and forming anti-stiction bumps at dimples (Fig. (2)). Parylene (5 μm) is deposited and etched by O_2 plasma (Fig. (3)). Finally the sacrificial layer of amorphous silicon is dry etched by XeF_2 gas to release mass and beam parts **[8]**. Isotropy dry etching by XeF_2 gas is effective for avoiding stiction (Fig. (4)). An examples of SEM image of a fabricated structure of accelerometer is shown in **Fig. 8**.

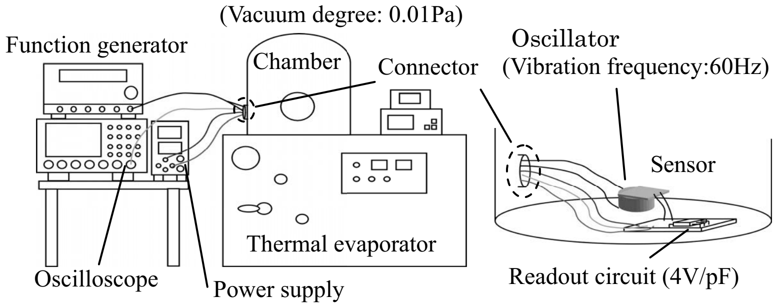


Figure 9: Experimental setup for acceleration measurement

The sensitivity is characterized by an experimental setup as shown in **Fig. 9**. The sensor is vibrated by an oscillator. Vibration frequency is set to 60 Hz and vacuum degree is about 0.01 Pa. The capacitance change is detected with the aid of a readout IC (MicroSensors Inc., MS3110), which converts capacitance change into voltage. The relationship between the voltage applied to oscillator and the generated acceleration is calibrated by a commercial accelerometer (EMIC Corp., 540-E). An example of waveforms is shown in **Fig. 10**. Sensor output has phase delay of 180 degrees compared with applied voltage, which proves this sensor is surely detecting acceleration. Changing applied voltage amplitude, sensor output amplitude is evaluated. An example of result is shown in **Fig. 11**. In this case the measured structure is with straight beams (same as already shown in **Fig. 8**). Although slight error exists, this sensor basically can detect acceleration with good linearity.

The performance of the accelerometer with spiral shaped beam is also evaluated. **Figure 12** shows the comparison between output of sensor with straight beams

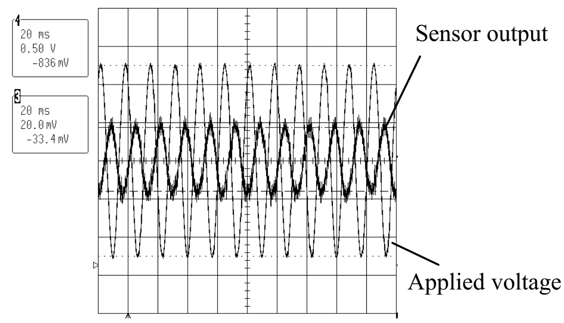


Figure 10: Relationship applied voltage and sensor output

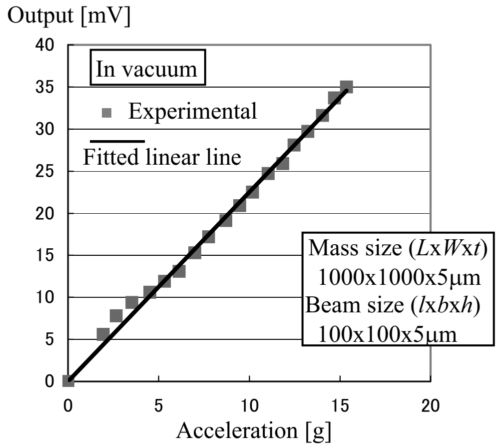


Figure 11: Relationship between acceleration input and sensor output

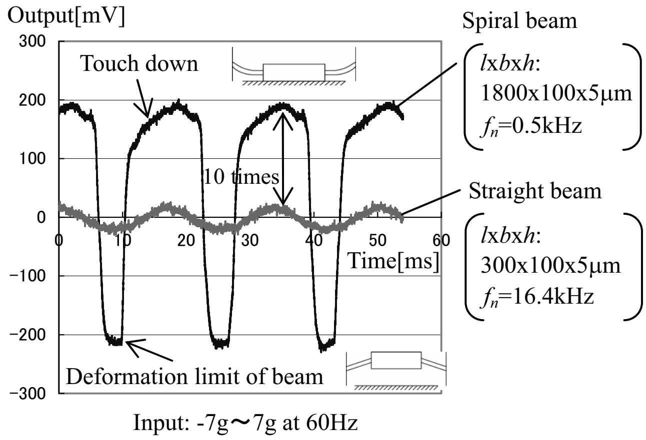


Figure 12: Output comparison between structure with straight beams and that with spiral beams

and that with spiral beams. Seeing this figure, sensitivity of the structure with spiral beams is about 10 times as high as that with straight beams, which confirms the effectiveness of spiral beams experimentally. The waveform distortion of the output of the spiral beam structure is supposedly caused by touch down of the mass to the substrate, deformation limit of beams, etc. according to large amplitude.

4. CONCLUSION

In this study, Parylene accelerometer utilizing spiral beams is fabricated in order to increase the sensitivity. First, the resonant frequency of the Parylene suspended structure is investigated. It is found that the resonant frequency of a suspended structure supported by straight beams is proportional to $1/l^{0.4}$ both theoretically and experimentally. Considering the sensitivity of accelerometer is $1/\omega_n^2$, comparatively long beams are necessary for realizing the high sensitivity. Spiral beam is effective for not only realizing a long beam in a limited space, but also realizing stress relaxation.

Second, several accelerometers with straight beams and with spiral beams are fabricated. These sensors basically can detect acceleration with good linearity. And it is experimentally confirmed that the sensitivity of the structures with spiral shaped beams is higher than that of the structures with normal straight beams.

ACKNOWLEDGEMENT

This work was mainly supported by JSPS (Japan Society for the Promotion of Science).KAKENHI (16310103). This work was also partially supported by MEXT (Ministry of Education, Culture, Sports, Science and Technology). KAKENHI (17656090), "High-Tech Research Center" Project for Private Universities: Matching Fund Subsidy from MEXT, 2000-2004 and 2005-2009, the Kansai University Special Research Fund, 2004 and 2005.

REFERENCE

[1] Y. C. Tai, “Parylene MEMS: Material, Technology and Application”, Proc. 20th Sensor Symposium, pp.1-8, 2003.

[2] S. Aoyagi and Y. C. Tai, “Development of Surface Micromachinable Capacitive Accelerometer Using Fringe Electrical Field”, Proc. Transducers’03, pp. 1383-1386, 2003.

[3] T. A. Harder, T. J. Yao, Q. He, C. Y. Shih and Y. C. Tai, “Residual Stress in Thin-Film Parylene-C”, Proc. MEMS’02, pp. 435-438, 2002.

[4] For example, G.Kovacs, “Micromachined Transducers Sourcebook”, McGraw-Hill, 1998.

[5] S. Aoyagi, D. Yoshikawa, K. Makihira and Y. C. Tai, “Study on Stiffness and Resonant Frequency of a Parylene Suspended Structure”, Proc. IMECE’04, CD-ROM no.61472, 2004.

[6] For example, S. P. Timoshenko, S. W. Krieger, “Theory of Plates and Shells”, McGraw-Hill, 1959.

[7] FEMLAB3 User’s Guide, Comsol, COPYRIGHT1994-2004.

[8] T. J. Yao, Q. He, X. Yang and Y. C. Tai, “BrF3 Dry Release Technologies for Large Freestanding Parylene”, Proc. Transducers’01, pp. 652-655, 2001.